PREDICTION OF CORRIDOR SMOKE FILLING
BY ZONE MODELS

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Abstract—Several zone models which are being used to predict the growth and spread of fires in compartments have been examined. We have benchmarked these models against a set of experiments which were designed to isolate the phenomenon of smoke filling in a room adjacent to a fire source, and connected by a variable opening. Good agreement is achieved between multi-compartment models and experiment. As an adjunct, we have implemented correlation based on a simple theory which collapses all of the data into a single graph by using dimensionless groups. These groups then contain most of the significant variables important in describing the flow of a gas from one compartment to another.

INTRODUCTION

In recent years there has been considerable research activity in the area of smoke movement in multicompartment structures as indicated by the list of references. The work is motivated by a need to understand and be able to predict the environmental conditions which occur as a fire develops and spreads. Much of the attention has focused on the development of numerical models which are able to make reasonably accurate predictions from the time of ignition. The motivation is two-fold. Being able to correlate laboratory scale experiments with full-scale tests is desirable from a cost standpoint. More importantly, from a life-safety and operational standpoint, the ability to make accurate predictions of the spread of smoke and fire opens up many possibilities for combating these problems, as well as taking effective preventive measures.

As these analytical tools are developed, it is important to insure that they are accurate. A corollary to this is that as our understanding of fire processes grows, we will gain confidence in the predictive capability of such models. Development of fire growth models is proceeding in several directions. One of the more important is verification and calibration against experimental work, and benchmarking of the algorithms against known numerical (or analytical) solutions. This paper examines several "state-of-the-art" multi-compartment models and compares them with experimental data. As part of the analysis, we have applied the concept of dimensionless groups to the variables of interest so that we might consolidate numerical results from both models and experimental data. This has led us to a simple correlation that could have practical use as a tool in developing a risk assessment.

BASIS OF THE MODELS

The basis for these models is the concept of the zone or control volume. This implies an integral formulation, for the zones are simply volumes whose surfaces encompass a space whose properties are approximately uniform. The postulate is that details

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within each of these zones are not important. The zones are then coupled to each other in an appropriate way. Of course, this sort of approximation leaves out processes which can be significant. For example, the detailed circulation around a burning object, or the turbulent entrainment in a plume. The gain, however, is significant. We require only a few equations to describe each compartment. Thus, the gain is realized in a reduction in computer resources required to solve a particular problem.

Most models being developed today center on the concept of a hot (upper) and a relatively cold (lower) layer for each compartment. These layers or zones are connected by mass and enthalpy flows between the compartments and heat transfer between the gas and walls. An approximation is that the lower layer is diathermous and usually at ambient temperature. For the early stages of a fire in a room this is a reasonably good approximation. However, for pressurized compartments or for situations where significant mixing can occur, such as small compartments with small openings, the physical changes in the lower layer should be included.

A model of a compartment fire can be broken down into the conservation equations with source and sink terms for each zone, and the subsidiary equations which describe the interactions between zones. To the model we must also apply the initial and boundary conditions.

Representative conservation equations for mass and energy can be written as,

$$\frac{dm}{dt} = \sum_i \dot{m}_i \tag{1}$$

and,

$$c_v m \frac{dT}{dt} - V \frac{dP}{dt} = \dot{Q} + \sum_i h_i \dot{m}_i \tag{2}$$

with an equation of state,

$$P = \rho R T \tag{3}$$

This equation of state is not complete; however, to the accuracy of the other approximations it is sufficient.

Strictly speaking, pressure is a function of height,

$$P(z) = P_{ref} - \int_0^z \rho(T) g \, dz \tag{4}$$

but within the framework of the integral approximation,

$$P(z) = P_{ref}$$

with P_{ref} the pressure at the floor or base of the compartment. It is only to estimate flow through openings that we need to use the full pressure term, namely the right-hand side of the equation (Tanaka, 1980). For other calculations, the use of the reference pressure is sufficient.

The terms $\dot{m}_i$ refer to source and sink terms of mass per unit time (dm/dt). The term h_i is the enthalpy associated with a particular mass parcel, usually not including the energy of formation. Finally, the $\dot{Q}$ is a generic term for radiative and convective heat losses and gains and heat release from the fire. Clearly when we write down the set of Eqs. (1)–(3) for each zone, the source and sink terms will be different. These details are adequately described by most of the references, which also discuss the various models in detail.

Only the conservation of mass and energy equations are solved for zones within a compartment. It is assumed that gas velocity is small within a compartment. Thus, only momentum transfer at the boundaries is considered. This is done by application of Bernoulli's equation at the openings. Tanaka (1980), Jones (1983), Zukoski et al. (1981) and Rocket (1976) give more detailed analyses. One term which is not well handled by any of the models is the mixing which occurs at vents. In contrast, plume entrainment is much better understood and predicted (Zukoski et al., 1981). Mixing within vents is an area of current research.

EXPERIMENTAL RESULTS

The series of tests which serve as a data-base for this analysis are based on a two-room fire scenario experiment (Cooper et al., 1981). The two rooms consisted of a fire (or burn room) and a second closed compartment (corridor). The experiment is conceptually simple, although somewhat elaborate in instrumentation. It was designed to examine specifically the problem of flow from one compartment to an adjacent compartment. The corridor was designed with an intentional leak and an effort was made to seal cracks and other uncalibrated leaks in the bounding surfaces. The parameters which were varied are the fire size and the width of the connecting door between the corridor and the room.

The floor plan area and total volume of the burn room were fixed at 14.0 m² and 32.2 m³, respectively. The plan area and volume of the corridor were varied from 26.6 m² to 48.4 m² and 61.2 m³ to 112.3 m³, respectively. A fire was simulated with a 0.3 × 0.3 m methane diffusion burner positioned 0.24 m above the floor. A tracer gas of ZnCl in the form of a smoke bomb, was used to simulate smoke and make visualization of the layer effect possible. The fire size was constant for each test and ranged from 25 kW to 225 kW for the various tests. The experiment also investigated a ramp fire to 300 kW, but that will not be discussed here.

The vent or "designed leak" from the corridor to the environment was fixed at 0.15 × 0.95 m. The standard door, 1.07 × 2.0 m, was used as a connecting vent, as were doors 1/2, 1/4 and 1/8 of the width (1.07 m).

A schematic of the experimental layout is shown in Figure 1. Figure 2 is a photograph during one of the experimental runs. This demonstrates a fairly sharp interface between the air and smoke, lending credence to the use of zone models in such fires. Measurements were made using thermocouples, photometers and visual readings, the latter being done with television cameras and tape recorders. Measurements were made in each room as well as in the connecting vent.

The temperature (and opacity) in each layer was not uniform, so some criterion was necessary to establish the interface between the hot and cold zones. A change of 10, 15 and 20 percent from the uppermost thermocouple or photometer was used (Cooper et al., 1981). The "layer" really represented a thermocline and, therefore, these criteria simply specified the effective discontinuity.
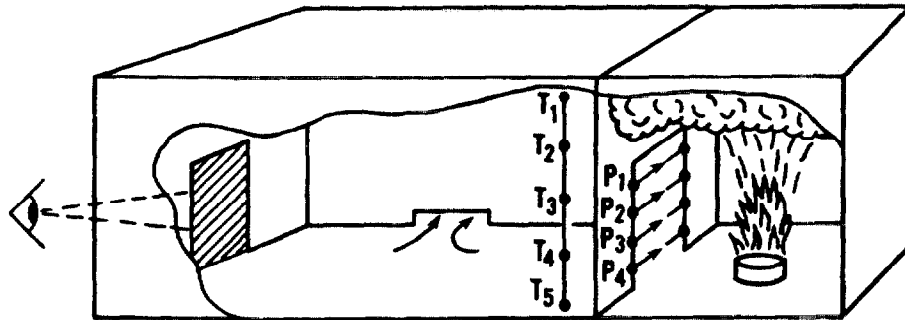
FIGURE 1   Schematic of the experimental test facility. The "eye", thermocouple tree "T" and photometer tree "P" are shown to indicate the type of data acquired.

ANALYSIS

A zone model can be characterized by whether it is applicable to a single compartment or multiple compartments. The former can be used to make global predictions for these experiments but the latter is required to make detailed temperature and layer height predictions for the individual rooms and to analyze the connectivity problems. The variables of interest which are predicted by these models are the upper layer temperature and the interface height.

Using the results from the 100 kW test. Figure 3 shows a comparison of measured layer height (Cooper et al., 1981) with several predictive models: a single-space model based on a leaky compartment (Cooper, 1981), a model designed for a single compartment (Mitler and Emmons, 1981) and a two-compartment model (Zukoski and Kubota, 1980). The single-compartment models were applied using the total volume and area in the experiment as the volume and area in the single compartment. The comparison of the single-compartment model prediction is with the layer height in the second room (corridor). Since a true thermal discontinuity does not exist in the experiments, the location of the interface between the two zones is a function of the criterion used. Results for the thermocouples, photometers and visual estimates are shown. The visual data (V) lags because it refers to the time at which the light sources are obscured by the smoke, the interface having already passed. Two criteria for the discontinuity position on the thermocline and the "photocline", namely a 10 and a 20 percent variation, are used. As can be seen, even the one-compartment model does a creditable job of predicting the smoke layer height.

However, a one-room model does not account for the connecting doorway, or for differences in the ceiling height of the two rooms. Additional experiments, where the size of the connecting doorway was varied. show the effect of changing geometry. Once again, the 100 kW fire was used. The door height remained constant at 2.0 m but the width was varied from 1.07 m (full) to 0.13 m (1/8). A comparison of the

FIGURE 2   Photograph of the test facility. The ZnCl tracer shows the stratification.

experimental and theoretical results is shown in Figure 4a, b, c. For these compari-
sons, both the layer height and the temperature of the upper layer is plotted for both
rooms. The results of two multi-room models (Zukoski and Kubotu, 1980; Tanaka,
1982) are also shown. The agreement is excellent, the only significant variation being
for the temperature in the burn room for the smallest (quarter) doorway. Since they
yield good results for this particular smoke filling problem, it would be useful to
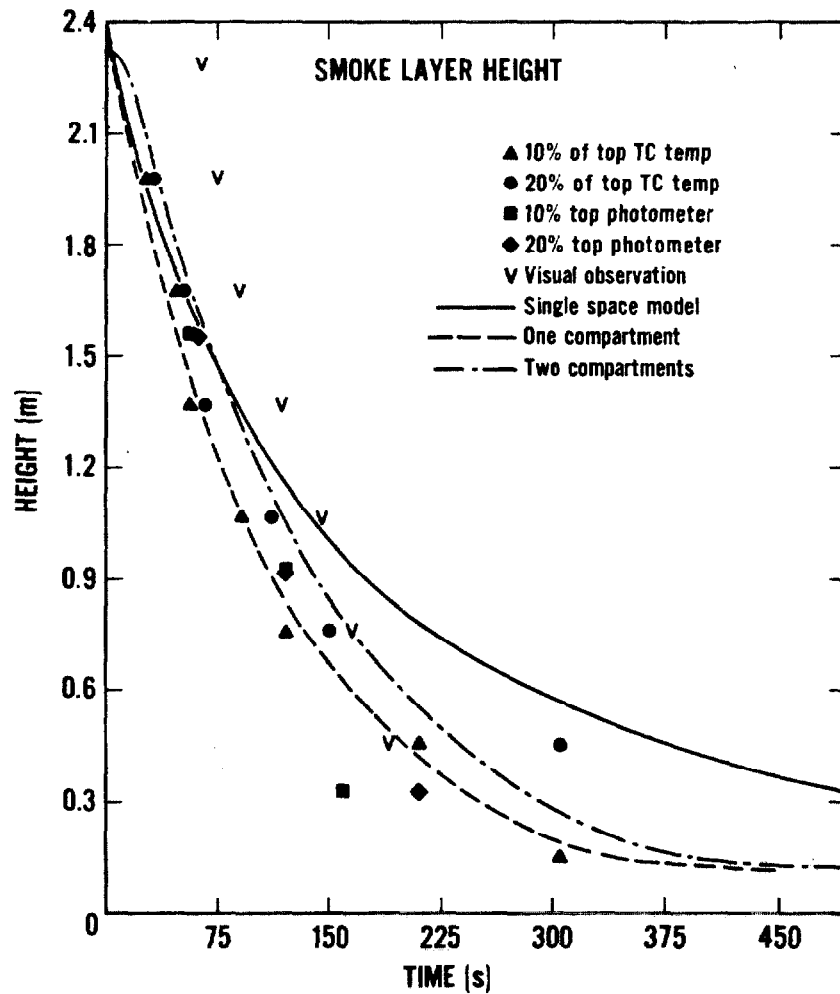
FIGURE 3 Comparison of the smoke layer height in the corridor. The experimental heights, as defined in Cooper *et al.* (1981) are shown as are the results of three different types of models (Zukoski and Kubota, 1980; Cooper, 1981; Mitler and Emmons, 1981). The data are for the 100 kW fire with a fully open door (1.07 m). (TC is an abbreviation for thermocouple.)

develop simpler relationships which could correlate the computer results as well as the experimental data.

SIMPLE THEORY

Consider a fire growing in the configuration shown in Figure 5. We can estimate the time required to fill the corridor based on a simple theory of filling (Zukoski,
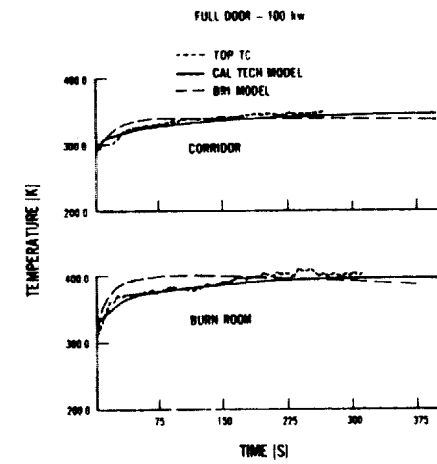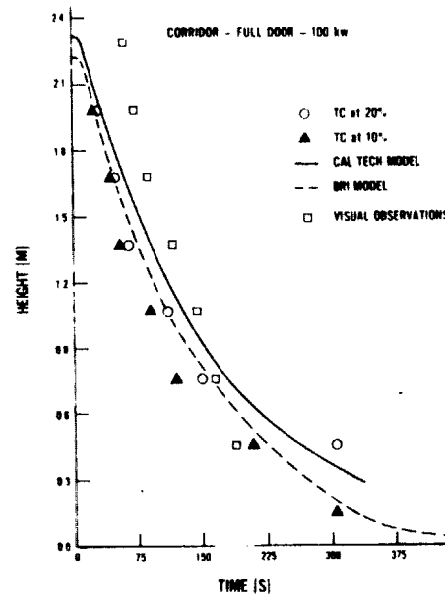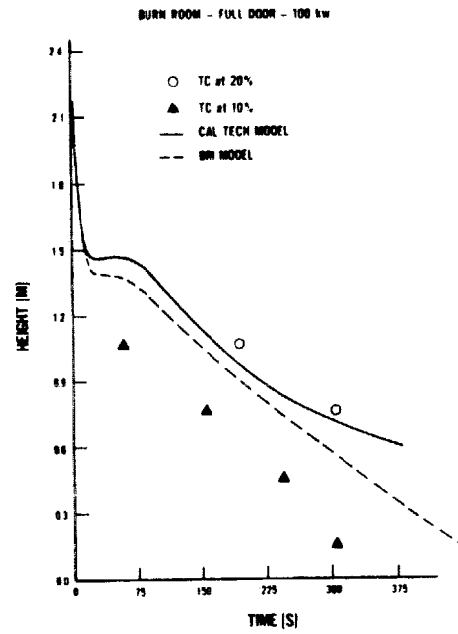
FIGURE 4a

BURN ROOM - HALF DOOR - 100 kw

- ○ TC at 20%
- ▲ TC at 10%
- —— CAL TECH MODEL
- — — BRI MODEL

HEIGHT (M)

TIME (S)

CORRIDOR - HALF DOOR - 100 kw

- ○ TC at 20%
- ▲ TC at 10%
- —— CAL TECH MODEL
- — — BRI MODEL
- ▢ VISUAL OBSERVATIONS

HEIGHT (M)

TIME (S)

HALF DOOR - 100 kw

- ····· TOP TC
- —— CAL TECH MODEL
- — — BRI MODEL

CORRIDOR

BURN ROOM

TEMPERATURE (K)

TIME (S)
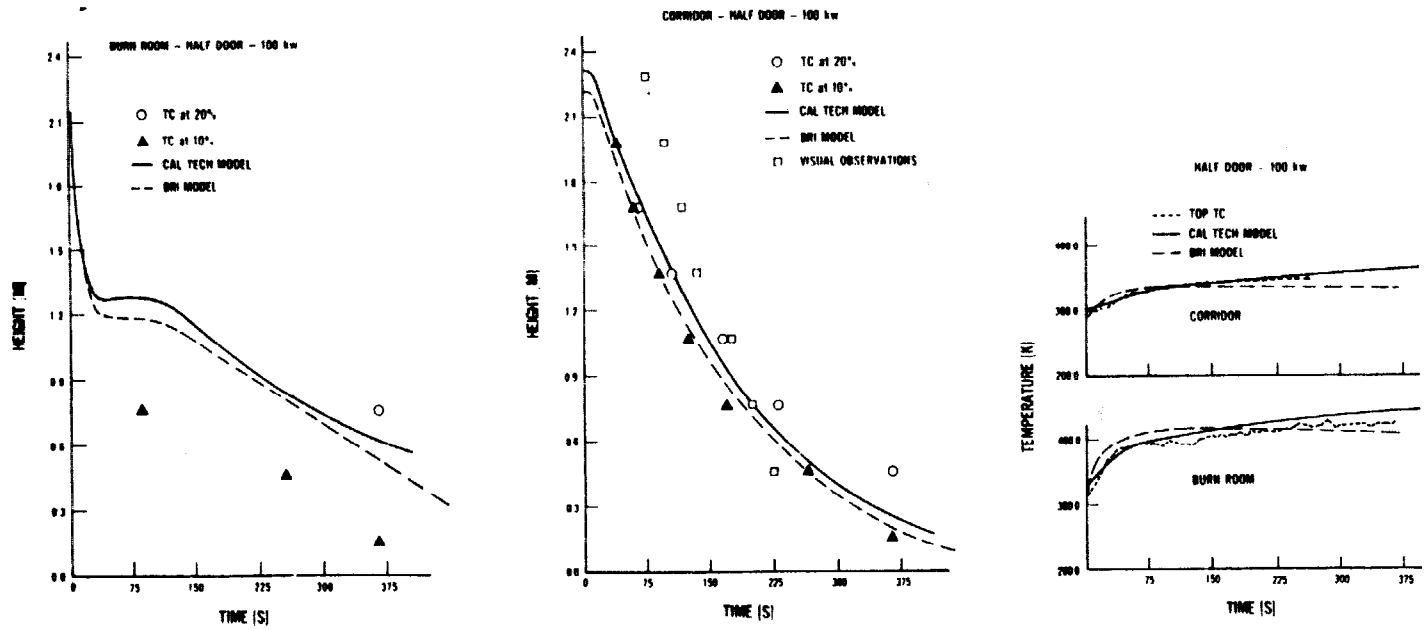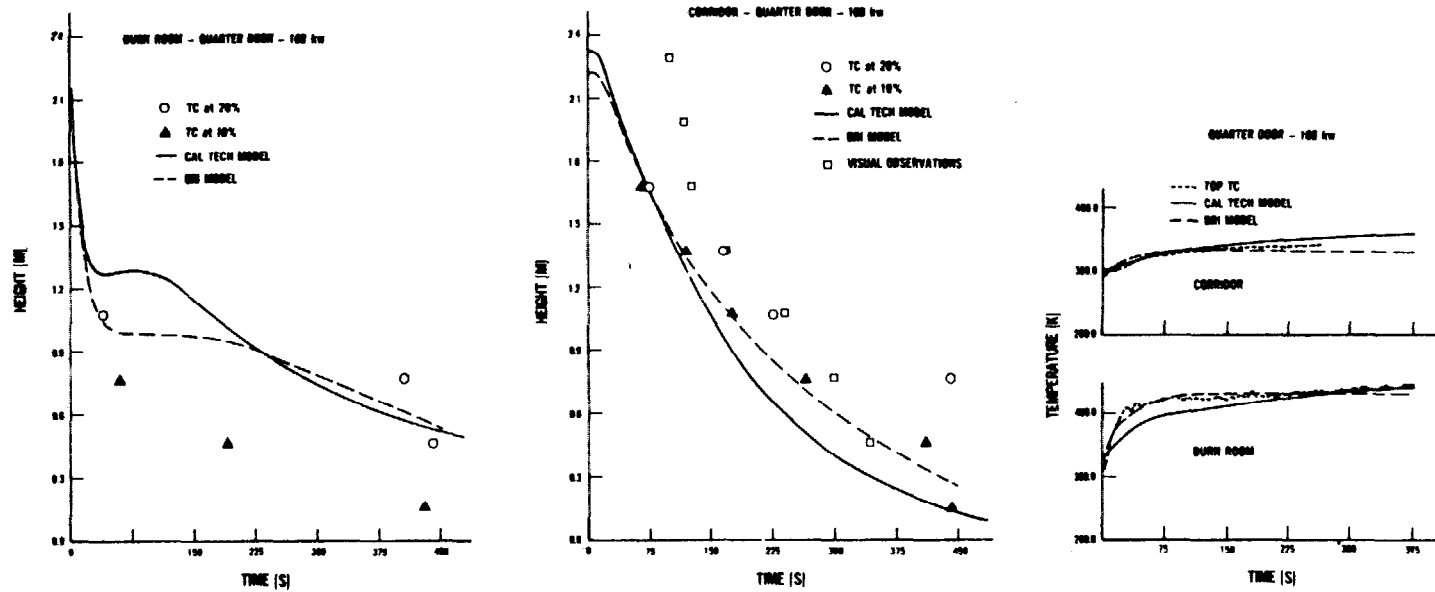
FIGURE 4b

FIGURE 4c

FIGURE 4 Graphs which show the experimental data and results of two models (———) Cal Tech Model (Zukoski *et al.*, 1981), (– – –) BRI (Tanaka, 1982) for the 100 kW fires. (A) fully open door (1.07 m); (B) half-door (0.58 m); (C) quarter-door (0.27 m). Corridor layer height, burn room layer height, corridor upper layer temperature and burn room upper layer temperature are shown respectively.
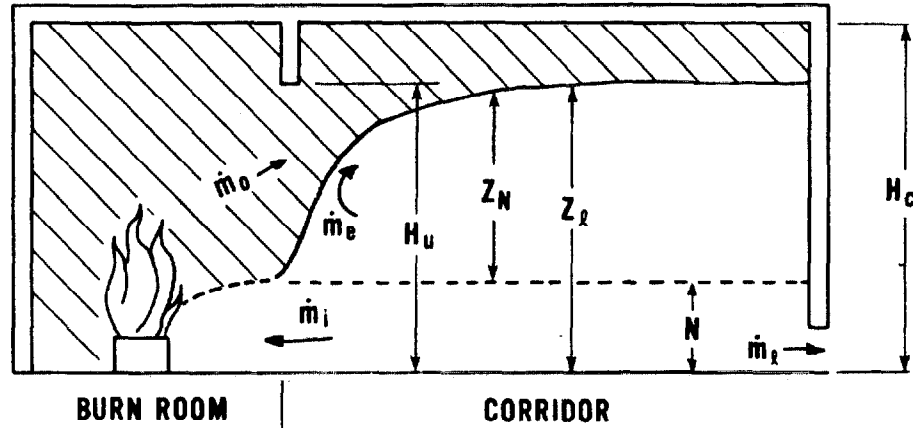
FIGURE 5   Visualization of the simple model showing schematically the flow out of the lower layer. The symbols are defined in Nomenclature.

1978a). We start with the equation for the conservation of mass for the lower layer in the corridor

$$\frac{d}{dt}(\rho_a Z_l A) + \dot{m}_i + \dot{m}_e + \dot{m}_l = 0.$$ (5)

That is, the disappearance of the lower (volume) is controlled by the leak at the floor vent to the outside ($\dot{m}_l$), the door-jet entrainment ($\dot{m}_e$) and the flow into the room ($\dot{m}_i$). If we allow two assumptions, the problem becomes quite tractable. First, assume that the door-jet acts like a point source symmetric plume in the corridor; second, that the neutral plane (N) remains approximately constant. The latter assumption breaks down very early and very late in the filling process but is a good approximation for most of the duration of the filling. The former is consistent with approximations currently used in multicompartment models.

We can now look for characteristic scales for this problem by rewriting Eq. (5) in terms of the variables,

$$\overset{*}{m} = \rho_a \sqrt{(gH_c)}H_c^2 = \text{characteristic mass flow}$$

$$\tau = t(\overset{*}{m}/\rho_a A H_c), \quad \text{and} \quad y = Z_l/H_c$$

where t is the time and H_c the corridor height. This model is based on the idea that the burn room is simply a source of hot gas, controlled by the air from the corridor. We use the following approximations for the source terms (Tanaka, 1980; Zukoski, 1978a; Zukoski, 1978b)

$$\dot{m}_i = \dot{m}_0 = \frac{2}{3}CBH_u^{3/2}\rho_a\left\{2g\frac{T_a}{T_g}\left(1 - \frac{T_a}{T_g}\right)\right\}^{1/2}\left(1 - \frac{N}{H_u}\right)^{3/2},$$ (6)

$$\dot{m}_c = 0.21(\overset{*}{Q})^{1/3} \rho_a \sqrt{(gZ)}Z^2, \quad Z = Z_l - N, \tag{7}$$

$$\dot{m}_l = \dot{Q}/C_p T_a \tag{8}$$

and

$$\overset{*}{Q} = \dot{Q}/C_p T_a \overset{*}{m}$$

where C is the flow coefficient (a value of 0.67 was used for these calculations) and B is the door width.

Equation (8) is true since the enthalpy leaving the room from the lower layer at T_a must be the same as the energy added to the upper layer assuming no loss to the wall. Zukowski (1978a) shows that the filling time is not strongly dependent on $\dot{Q}$ for a floor leak.

By substituting Eqs. (6)–(8) in Eq. (5) and expressing the result in dimensionless variables, we obtain

$$\frac{dy}{d\tau} + C_1 + C_2 y^{5/2} = 0 \tag{9}$$

which holds for $y = 1.0$ to N/H_c with $y = 1$ at $\tau = 0$. The experimental conditions, $N \sim 1/2$ m, $T_g \sim 350$ K, $T_a \sim 293$ K, the coefficients are approximately,

$$C_1 = 0.11\, BH_u^{3/2}/H_c^{5/2} + \overset{*}{Q} \simeq 0.11\,\overset{*}{P} + \overset{*}{Q}$$

and

$$C_2 = 0.21\, \overset{*}{Q}^{1/3}.$$

This indicates that the dimensionless filling time, $\tau(y = N/H_c)$, is a function of the dimensionless heat release rate ($\overset{*}{Q}$) and should correspond to the parameter

$$\overset{*}{P} = BH_u^{3/2}/H_c^{5/2}.$$

Table 1 is a tabulation of these parameters derived from both the experimental values (Cooper et al., 1981) and one of the multiroom models (Tanaka, 1982), the criterion for the both being the time for the layer to reach 1.07 m from the floor. The values given in parenthesis are for three floor-plan areas of the corridor (26.4, 37.4 and 48.0 m², respectively).

Both experimental and model results are plotted in Figure 6. The open symbols are the experimental data and the closed symbols the modeling results. The results include experiments where the door size was fixed (1.07 m) and the fire size varied 25–225 kW) and for a fixed fire (100 kW) and a variable door (0.13–1.07 m). For the cases where overlap occurred (results for three floor-plan areas are shown) in plotting the data, an attempt was made to include a representative sample from both at each value of $\overset{*}{Q}$. The solid lines shown are for a consistent set of model results,

TABLE I

Dimensionless filling time in terms of $\overset{*}{Q}$ and $\overset{*}{P}$

$\overset{*}{P}$	$\overset{*}{Q} \times 10^{-3}$	Computed results (Tanaka, 1982)		Experimental results (Cooper et al., 1981)	
		τ	$\bar{\tau}$	τ_{exp}	$\bar{\tau}_{exp}$
0.370	2.7	(56, 52, 50)[a]	53	(43, 36, 50)	43
	8.1	(36, 32, 31)	32		
	11	(32, 30, 29)	30	(23, 24, 19)	22
	16	(28, 26, 25)	26		
	24	(23, 23, 23)	23	(25, 21, 20)	22
0.180	11	(37)	37	(38)	38
0.092	11	(41)	41	(52)	52
0.065	0.48	(71, 63, 60)	65		
	1.4	(41, 37, 35)	37		
	1.9	(37, 33, 31)	33		
	2.8	(31, 27, 27)	28		
	4.3	(28, 24, 23)	25		
0.046	2.6	(122)	122		
	8.1	(72, 70)	71		
	11	(64, 63, 63)	63	(69)	69
	16	(54, 54, 54)	54		
	24	(44, 44, 44)	44		

Q ranged from 25 kW to 225 kW.

B ranged from 1.07 m (full door) to 0.13 m (1/8 door).

H_c was 2.32 m.

$\overset{*}{Q}$ ranged from 0.48×10^3 to 24×10^3.

[a] For the values given as sets, a measurement or calculation was done for one, two or three floor plan areas (26.4 m², 37.4 m², 48.0 m²) and the $\bar{\tau}$ is the average of these values.

however. Figure (7) shows model calculations for a corridor of height $2H_c$. Once again, the data are grouped according to the parameter, $\overset{*}{P}$.

CONCLUSIONS

The predictions of smoke movement by multicompartment models agree well with experimental data, at least for simple fire scenarios. What is needed now is to understand the more complicated multicompartment fire sources and multiply connected compartments. Also the correlation of filling time with the experimental parameters seems to be good in terms of our dimensionless groups. This allows one to make a reasonable estimate of the filling time for other experimental conditions.
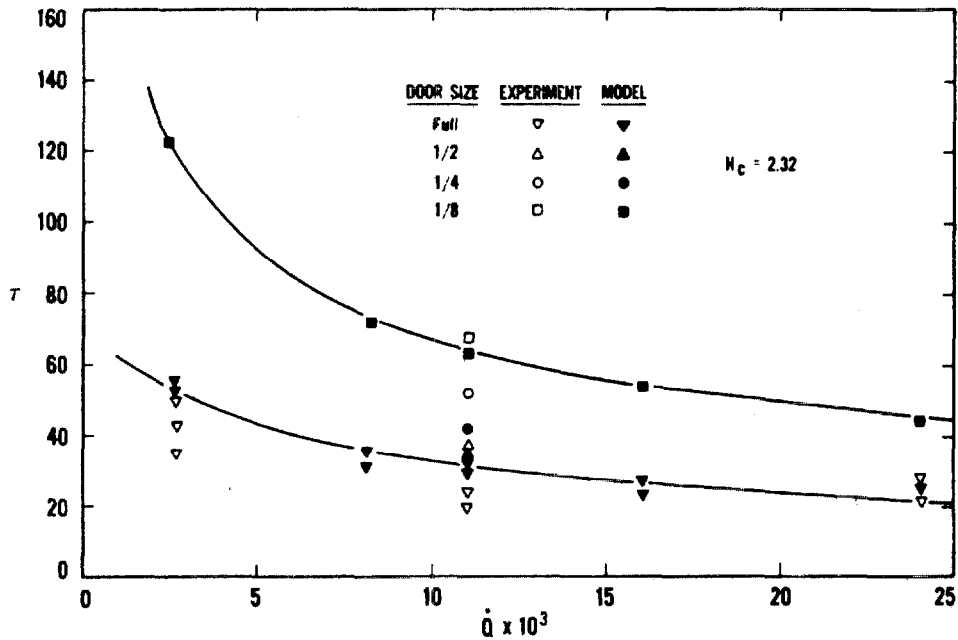
FIGURE 6 Plot of both experimental results (○) and the model calculation (●). The dimensionless time ($\bar{t}$) is plotted versus the dimensionless heat release rate ($\dot{Q}$). The results are plotted as a function of the parameter ($\dot{P}$). As can be seen from the model results ($\dot{P}=0.37$ is the open door, $\dot{P}=0.046$ is the eighth-door), the results should lie in a band. The experimental values generally confirm this conclusion.

NOMENCLATURE

$\dot{m}$	mass
$\dot{m}_t$	flow out of the corridor into the burn room
$\dot{m}_e$	mass entrained by the door jet
$\dot{m}_l$	mass loss by leakage
ρ	mass density (kg/m^3)
ρ_A	ambient density
c_p	specific heat (J/kg/K)
T	temperature (K)
$\dot{Q}$	net heat release rate (W)
$\dot{Q}$	dimensionless heat release rate—see text
h_t	enthalpy
P	pressure (P$_a$)
R	universal gas constant (289 J/kg/K for air)
H_u	top of connecting vent (m)
H_c	height of corridor (m)
t	time (s)
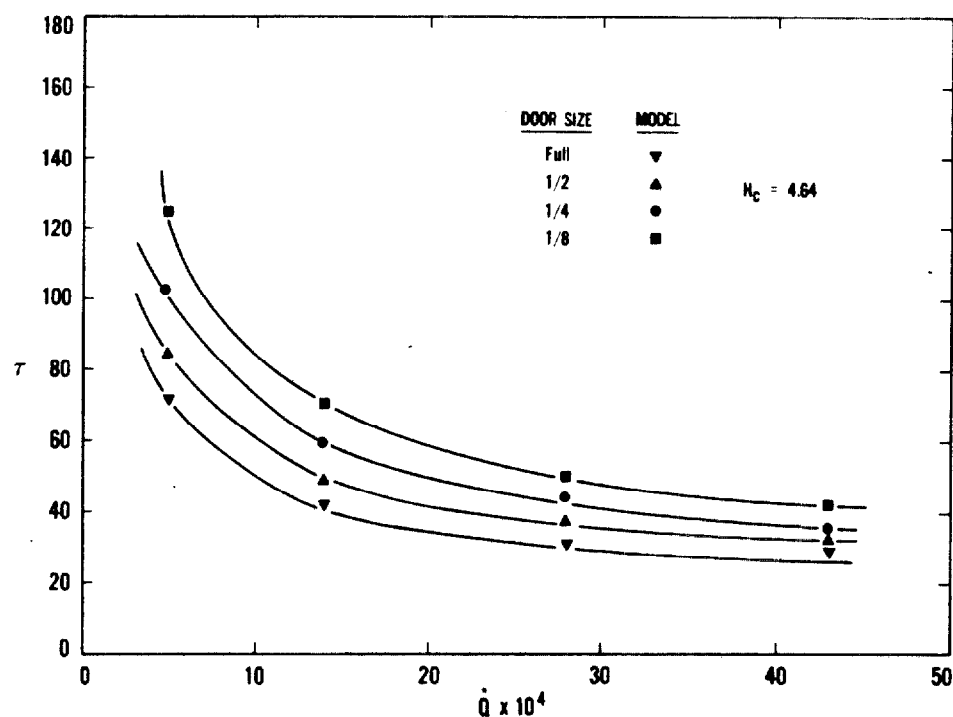
FIGURE 7   Model results for a corridor of height $H_c = 4.64$.

τ	dimensionless time—see text
P^*	scaling parameter—see text
y	dimensionless height—see text
Z_l	lower zone thickness
Z_N	thickness between the neutral plane (N) and the top left of the lower zone
N	height of the neutral plane

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